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EXAMINATION OF THE INLET
ROLLED JOINT FROM
NPD FUEL CHANNEL F08

by

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Research report

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ROLLED JOINT FROM NPD CHANNEL F08

A report prepared by R.R. Bawden and J.P. Slade of Atomic Energy of Canada Limited, under contract to the Atomic Energy Control Board.

ABSTRACT

Visual examination of the inlet rolled joint from NPD fuel channel F08 revealed corrosion damage on the mating surfaces of the pressure tube and end fitting. There was severe pitting on the inboard rolling groove on the end fitting. Hydrogen equivalent concentration, measured by isotope dilution, was 98 mg/kg and 145 mg/kg at 19.6 mm and 51.4 mm from the inlet end of the pressure tube respectively. Metallographic examination revealed the hydrides were uniformly distributed through the wall thickness and along the length of the rolled joint. Only minor concentration gradients were detected by image analysis. The through-wall gradients were random and could be related to the geometry or corrosion of the rolled joint. There was no pattern to indicate the path of the deuterium ingress.

RÉSUMÉ

En examinant visuellement le joint roulé des embouchures du canal de combustible F08 du réacteur NPD, on a découvert que la corrosion avait endommagé la surface d'accouplement du tube de force et du raccord d'extrémité. La concentration en équivalent d'hydrogène, mesurée par dilution des isotopes, était de 98 mg/kg et de 145 mg/kg à 19,6 mm et à 51,4 mm respectivement de l'extrémité de l'embouchure du tube de force. L'examen métallographique a révélé que des hydrures étaient distribués uniformément à travers l'épaisseur de la paroi et le long du joint roulé. Seules de faibles gradients de concentrations ont été décelés grâce à l'analyse par images. Les gradients à travers la paroi étaient distribués au hasard et pouvaient être imputables à la configuration géométrique ou à la corrosion du joint roulé. Il n'existait aucune indication montrant l'entrée de deutérium.

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1. INTRODUCTION

At the request of the Atomic Energy Control Board, the rolled joint from the inlet end of NPD fuel channel F08 was examined. The purpose of the examination was to use metallographic image analysis techniques to measure hydrogen concentration and to determine if concentration gradients indicate an ingress path, and to determine the effects of stress on hydride distribution in the rolled joint.

The pressure tube from NPD lattice position F08 was fabricated from Zircaloy-2 and was removed from reactor in 1987 after 25 years (156,900 EFPH) of service. The F08 pressure tube was selected because it had a high deuterium concentration of 471 mg/kg, 2.95 m from the inlet end of the tube [1]. The deuterium concentration in the rolled joint region was not known prior to this examination.

The project consisted of a visual examination of the mating surfaces between the pressure tube and end fitting, metallographic examination, image analysis, and hydrogen and deuterium analysis.

2. VISUAL EXAMINATION

A 40 mm wide axial strip of pressure tube and end fitting, from the in-reactor 12 o'clock position, was sectioned from the inlet end of the pressure tube. The mating surfaces of the rolled joint were separated after sectioning and were examined in the shielded hot cells. For ease of reporting the outboard (furthest from the reactor core), middle, and inboard (closest to the reactor core) rolling grooves will be referred to as the first, second, and third groove respectively.

The inside surface of the end fitting and the outside surface of the pressure tube from the rolled burnished mark to the third groove had a mottled appearance (Figure 1, Label A). We believe this is due to the open annulus in NPD, which had been wet during the operation of this reactor and resulted in corrosion in the crevice between the pressure tube and end fitting.

Severe pitting was observed on the end fitting in the third rolling groove (Figure 1, Label B). The pressure tube surface corresponding to this region showed no signs of corrosion (Figure 1, Label C).

The region between the second and third grooves was divided into a belt of mottled oxide adjacent to a band of normal oxide (Figure 1, Label D). This mottling was somewhat more pronounced than that observed inboard of the third groove. The pattern on the end fitting and pressure tube surfaces was similar.

The interface at the first groove, the region between the first and second grooves, and the interface at the second groove were in good condition with no evidence of corrosion on either the end fitting or pressure tube (Figure 1, Label E).

The region outboard of the first groove was in good condition, with only minor corrosion observed on the surface of the end fitting adjacent to the outboard edge of the first groove (Figure 1, Label F).

Plastic deformation of the pressure tube leading into the first and third grooves was observed (Figure 1, Label G and Figure 2, Label A). The deformation was more severe than observed on CANDU rolled joints.

3. METALLOGRAPHIC EXAMINATION

Four longitudinal metallographic sections incorporating the pressure tube from the outboard end of the pressure tube to inboard of the roll burnish mark were prepared. One transverse metallographic section was prepared from the inboard edge of the third rolling groove. All of the metallographic samples were taken from the 12 o'clock strip of pressure tube. The location of the metallographic sections are detailed in Figure 2. All of the sections were etched with a 90-90-8 nitric-lactic-hydrofluoric acid solution to allow examination of the hydrides.

Representative through-wall micrographs were taken at a magnification of 250X at the eight locations on the longitudinal sections (locations shown in Figure 2) and one location on the transverse section for image analysis. Micrographs showing typical hydride morphology at the inside surface, mid-wall, and outside surface for each of the through-wall composite locations are presented in Figures 3 to 11.

The hydride size, shape, and distribution were uniform through the thickness and along the length of the pressure tube in the rolled joint region, and were typical of pressure tube material having high deuterium concentration. There were no significant hydride gradients evident. There were no radial hydrides present on both the longitudinal or the transverse sections. Radial hydrides are not readily apparent on longitudinal metallographic sections.

4. IMAGE ANALYSIS

Measurements of through-wall hydrogen equivalent concentration were made on each of the nine through-wall composites. A Kontron image analyzing computer with an IBAS 2000 program was used to discriminate hydrides from noise and background on the photomicrographs; hydrides were modelled as linear features. The length of hydride per unit area was measured and equated to hydrogen concentration (mg/kg), using an equation developed by R.E. Sawden and the late J.F.R. Ambler. Approximately 120 measuring fields (0.2 mm x 0.2 mm) were processed from the inside to the outside surface. Each measuring field overlapped adjacent fields by 50% for continuity of the measurements. The results of the image analysis are presented in Table 1 and Figures 12 to 20.

Through-wall gradients were detected at the 19.6 mm, 56 mm, 51.4 mm, and 75.6 mm from the inlet end of the pressure tube, but in our opinion were not significant. The hydrogen concentration was lower at the inside surface at the 19.6 and 51.4 mm locations, and lower at the outside surface at the 56 and 75.6 mm locations. However, the hydrogen concentration was generally lower at the mid-wall region than at the surfaces. There was no pattern to indicate the path of deuterium ingress.

The average values of hydrogen concentration from each through-wall composite are presented in Figure 21. Linear regression of the average values showed a slight decreasing gradient from the inlet end of the pressure tube, as expected for a pressure tube rolled joint [2]. The average hydrogen concentration at the first and third rolling grooves was higher than the other measured locations, suggesting the deuterium ingress was higher at the rolling grooves.

The hydrogen-equivalent data from the through-wall measurements were segmented into eight groups from the outside to inside surfaces. The average value of each segment was plotted against axial position, shown in Figure 22. The axial profile for each of the through-wall segments was similar. The two segments in the middle of the tube wall thickness (37.5 to 50% and 50 to 62.5% through-wall) were generally lower than at the surfaces.

5. HYDROGEN AND DEUTERIUM ANALYSIS

Three punch samples were taken from the 19.6 mm and 51.4 mm locations from the inlet end of the pressure tube (the location relative to the rolled joint is shown in Figure 2). Two samples from each location were analyzed for deuterium and one for hydrogen concentration by isotope dilution.

The results of the hydrogen and deuterium analysis are presented in Table 2 and Figure 21. The hydrogen equivalent was 145 mg/kg (1.3 at%) at 19.6 mm and 98 mg/kg (0.88 at%) at 51.4 mm from the inlet end of the pressure tube. These analyses confirmed the decreasing gradient from the inlet end of the

pressure tube in the rolled joint. Such a large difference between two points along the rolled joint is not unusual; these results are typical of hydrogen isotope concentrations seen in other rolled joints [2].

6. DISCUSSION

Hydride gradients are expected only when the ingress rate is very high relative to the diffusion rate of deuterium in the pressure tube. In NPD and CANDU reactors the deuterium ingress rate has been low relative to the diffusion rate and therefore concentration gradients are not expected. Gradients have been observed in some rolled joint experiments. In laboratory experiments on rolled joints having titanium alloy hubs, blisters formed at the corners of the rolling grooves because of rapid migration of hydrogen from titanium to zirconium and because there was good contact between the pressure tube and the end fitting [2].

In the NPD F08 inlet rolled joint no significant gradients were detected. The hydrides, and therefore hydrogen concentration, were relatively uniform through the wall thickness of the pressure tube in the rolled joint region.

Through-wall gradients were evident at four locations on the micrographs, but were considered minor. The gradients appeared to be random and could not be related to the geometry of the rolled joint. Substantial corrosion damage was evident on the end fitting and pressure tube mating surfaces, but this damage could not be related to the hydrogen gradients. There was no pattern to indicate the path of deuterium ingress. There was a decreasing axial gradient from the inlet end of the tube in the rolled joint region as expected. The axial profile had peaks near the first and third rolling grooves.

The difference between image analysis results and isotope dilution results was very large, 41% and 162% at 19.6 and 51.4 mm from the inlet respectively. The IBAS 2000 program was developed for measurement of hydrides on transverse metallographic sections. We expected a large deviation from the actual hydrogen concentration on longitudinal sections using the existing measurement program. The primary source of the deviation is the difference in hydride length in the transverse and longitudinal directions. The correlation between image analysis measurements (on transverse sections) and actual hydrogen concentration has been good (within 10%) when the concentration was between 20 and 75 mg/kg. In this case, with the concentration being in excess of 100 mg/kg, the error in the image analysis measurements is substantial. However, the values obtained off the longitudinal sections of the rolled joint of NPD F08 can be compared with one another. Comparisons between the values from the longitudinal sections and the transverse section is not recommended.

6.1 Suggestions for Further Work

With further development, the inherent error in the image analysis technique for measuring hydrogen concentration can be reduced. The technique was satisfactory for this application, where through-wall hydrogen concentration gradients were the primary concern rather than absolute concentration. Image analysis would be a viable technique for examining Zr-2.5 Nb rolled joints with lower hydrogen content. Hydride gradients may be present in rolled joints early in service. A rolled joint from a fuel channel with a short service life (less than 2 years in-reactor) would be ideal for quantifying hydrogen gradients.

7. SUMMARY

Visual examination of the mating surfaces of the NPD fuel-channel F08 inlet rolled joint revealed crevice corrosion on the outside surface of the pressure tube between the roll burnish mark and the third rolled joint. The end fitting displayed severe pitting corrosion in the third rolling groove. Hydrogen equivalent concentration was measured by isotope dilution to be 145 mg/kg and 98 mg/kg at 19.6 mm and 51.4 mm from the inlet end of the pressure tube respectively. Metallographic examination revealed the hydrides were typical of Zircaloy-2 with high deuterium concentrations, and were uniformly distributed through the wall thickness and along the length of the rolled joint. Only minor gradients were detected by image analysis of the rolled joint. The through-wall gradients were random and could not be related to the geometry or corrosion of the rolled joint. There was no pattern to indicate the path of deuterium ingress.

8. REFERENCES

1. C.E. Coleman, B.A. Cheadle, A.R. Causey, C.K. Chow, P.H. Davies, M.D. McManus, D.K. Rodgers, S. Sagat, and G. van Drunen, "Evaluation of Zircaloy-2 Pressure Tubes from NPD", Accepted for publication in an ASTM STP.
2. Private communication with V.F. Urbanic.

TABLE 1
IMAGE ANALYSIS RESULTS

DISTANCE THROUGH- WALL	HYDROGEN EQUIVALENT CONCENTRATION (mg/kg, uncorrected)								
	DISTANCE FROM THE INLET (mm)								
	12.9	19.6	30.4	36.7	51.4	56.0	69.0	75.6	59.6*
(Outside)									
0.1 mm	232	233	319	287	263	285	217	176	172
0.2 mm	234	257	353	306	287	340	243	166	150
0.3 mm	301	234	336	292	291	269	221	167	162
0.4 mm	278	252	319	286	273	248	213	168	154
0.5 mm	242	257	326	283	258	270	219	183	155
0.6 mm	253	252	309	300	240	273	227	189	177
0.7 mm	285	257	321	294	245	273	219	187	165
0.8 mm	271	246	348	310	245	297	194	178	173
0.9 mm	253	239	329	290	241	323	196	180	179
1.0 mm	253	239	306	271	264	267	205	167	173
1.1 mm	244	192	311	287	263	267	185	173	171
1.2 mm	240	159	319	278	283	248	195	198	175
1.3 mm	235	203	318	263	283	238	190	192	146
1.4 mm	245	193	339	267	282	293	192	194	152
1.5 mm	258	126	332	257	222	286	189	214	170
1.6 mm	236	185	311	253	238	254	194	188	159
1.7 mm	255	150	311	268	289	258	200	133	153
1.8 mm	243	160	326	278	227	222	207	154	154
1.9 mm	234	186	323	288	258	237	207	198	137
2.0 mm	244	173	322	245	281	252	199	213	136
2.1 mm	249	172	304	235	255	250	182	216	133
2.2 mm	219	172	323	199	247	253	171	176	119
2.3 mm	237	168	308	218	274	274	183	154	138
2.4 mm	255	207	298	229	287	246	217	162	160
2.5 mm	240	194	319	258	274	270	232	217	133
2.6 mm	240	185	331	274	250	292	211	187	144
2.7 mm	249	196	353	276	254	315	198	155	154
2.8 mm	247	203	310	260	256	356	189	154	127
2.9 mm	262	197	327	237	303	344	170	216	149
3.0 mm	253	210	309	266	293	312	187	224	169
3.1 mm	290	220	300	286	261	345	184	211	136
3.2 mm	283	222	330	278	234	355	173	212	130
3.3 mm	256	192	322	289	240	309	164	199	136
3.4 mm	262	200	309	259	228	289	148	219	120
3.5 mm	278	196	306	261	206	317	160	209	128
3.6 mm	245	199	311	277	219	291	182	208	148
3.7 mm	255	237	313	270	246	279		191	150
3.8 mm			329		232	330		223	
3.9 mm			337		232	351		251	
4.0 mm			328			322		253	
4.1 mm								230	
4.2 mm								210	
4.3 mm								203	
4.4 mm								211	
4.5 mm								210	
4.6 mm								230	
4.7 mm								218	
(Inside)									
MINIMUM	219	126	298	199	206	237	160	133	119
AVERAGE	253	204	321	270	257	287	196	195	151
MAXIMUM	301	257	353	310	303	356	243	253	180

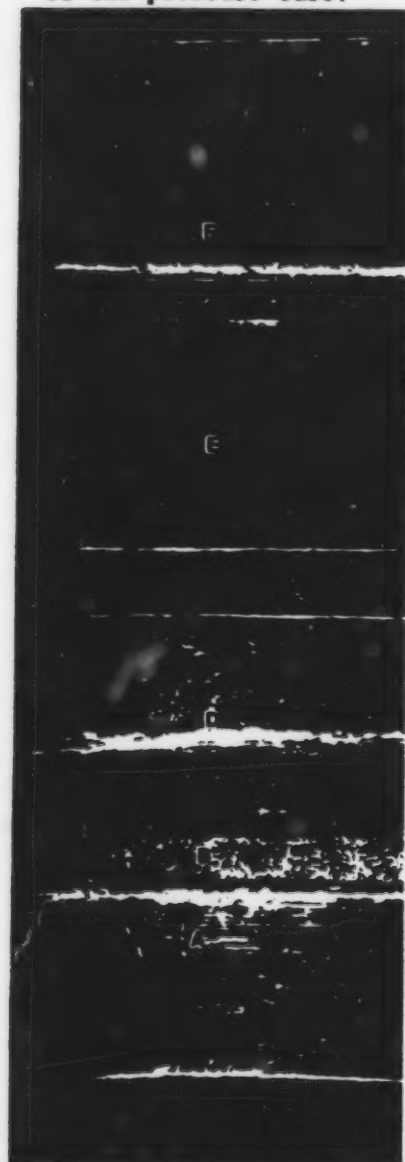
* Transverse metallographic section.

TABLE 2
HYDROGEN AND DEUTERIUM ANALYSIS

AXIAL LOCATION DISTANCE FROM THE INLET (mm)	HYDROGEN CONCENTRATION mg/kg (at%)	DEUTERIUM CONCENTRATION mg/kg (at%)	HYDROGEN EQUIVALENT CONCENTRATION mg/kg (at%)
19.6	23 (0.21)	246 (1.10) 240 (1.08)	145 (1.30)
51.4	19 (0.17)	159 (0.72) 158 (0.71)	98 (0.88)

Figure 1:

Mating surfaces of the 12 o'clock strip sectioned from the NPD F08 inlet rolled joint, showing the outside surface of the endfitting and the inside surface of the pressure tube.



END FITTING



PRESSURE TUBE

Outboard end

First groove

Second groove

Third groove

Inboard end

-- Outboard End

-- 12.9 mm

-- 19.6 mm

-- A - Region noted as G in Figure 1

-- First Groove

-- 30.4 mm

-- 36.7 mm

-- Second Groove

-- 51.4 mm

-- 56 mm

-- Third groove

-- Transverse met. section (59.6 mm)

-- A - Region noted as G in Figure 1.

-- 69 mm

-- 75.6 mm

-- Inboard End

Figure 2: Macrophotograph of the longitudinal metallographic sections, showing the profile of, and the axial ridge locations of the NPD F08 inlet rolled joint. Metallographic locations are marked by the distance in mm from the inlet end of the tube.

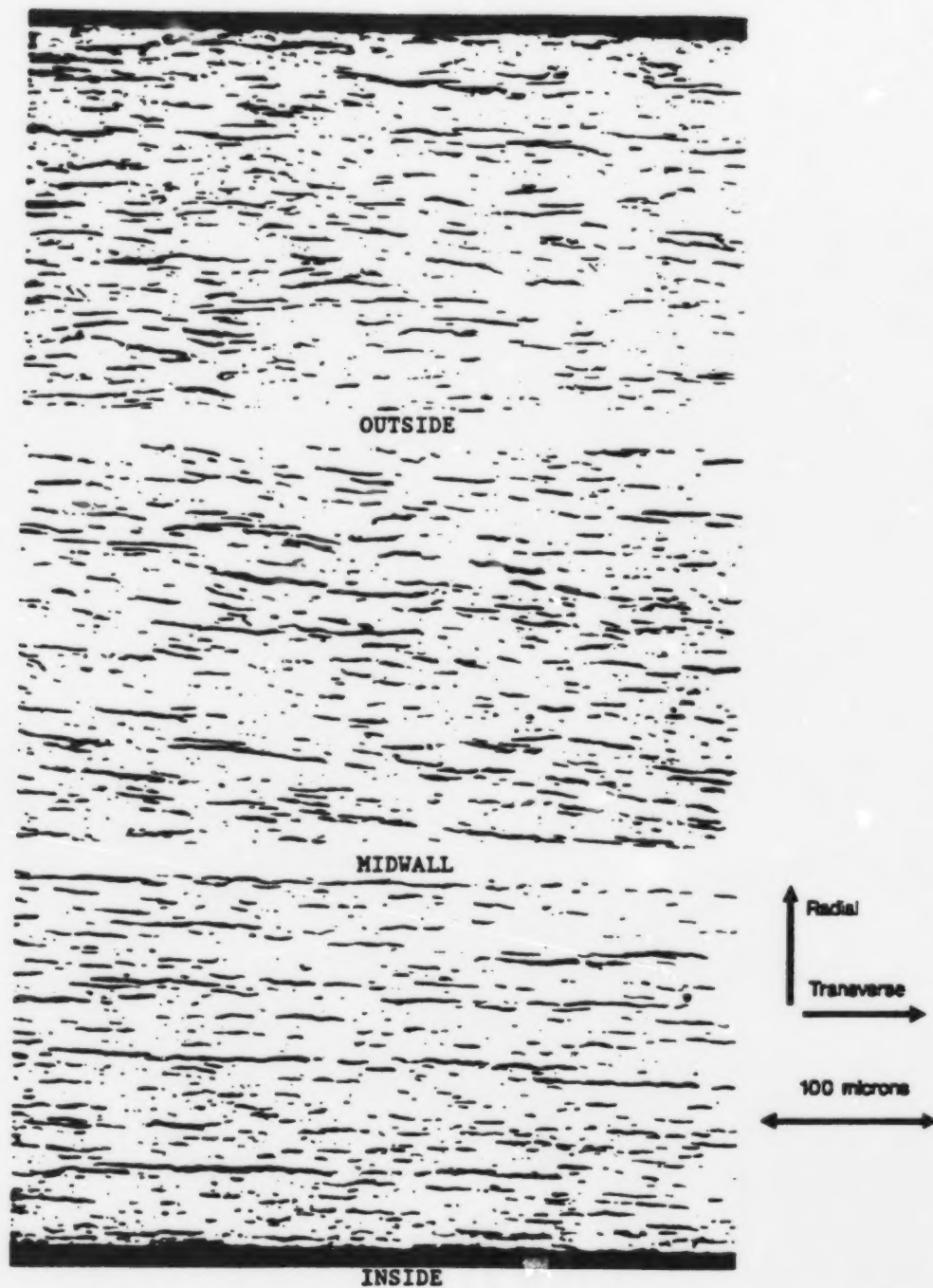


Figure 3: Representative outside, midwall and inside hydride distribution of the longitudinal section at 12.9 mm from the inlet end of the tube.

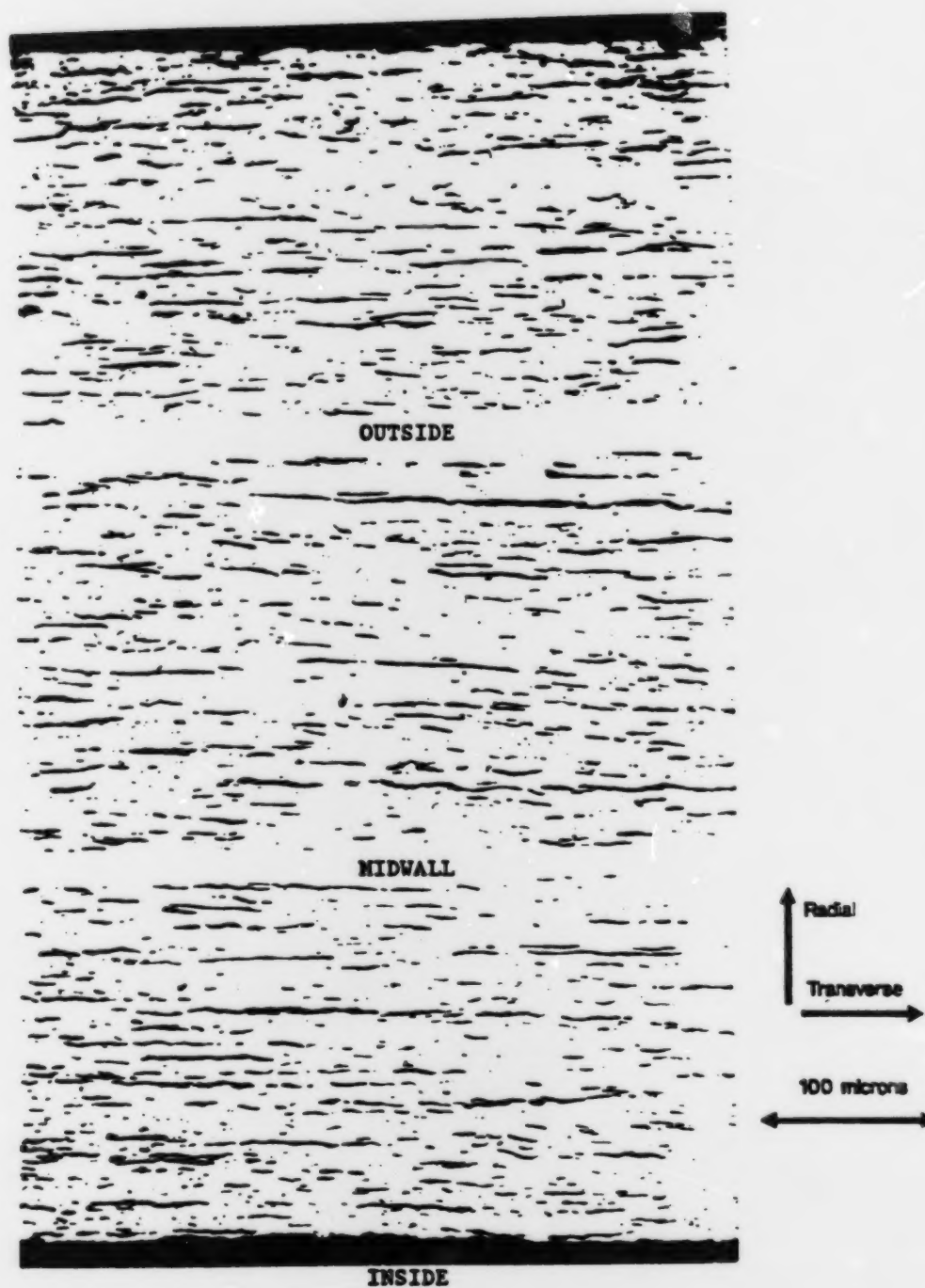


Figure 4: Representative outside, midwall and inside hydride distribution of the longitudinal section at 19.6 mm from the inlet end of the tube.

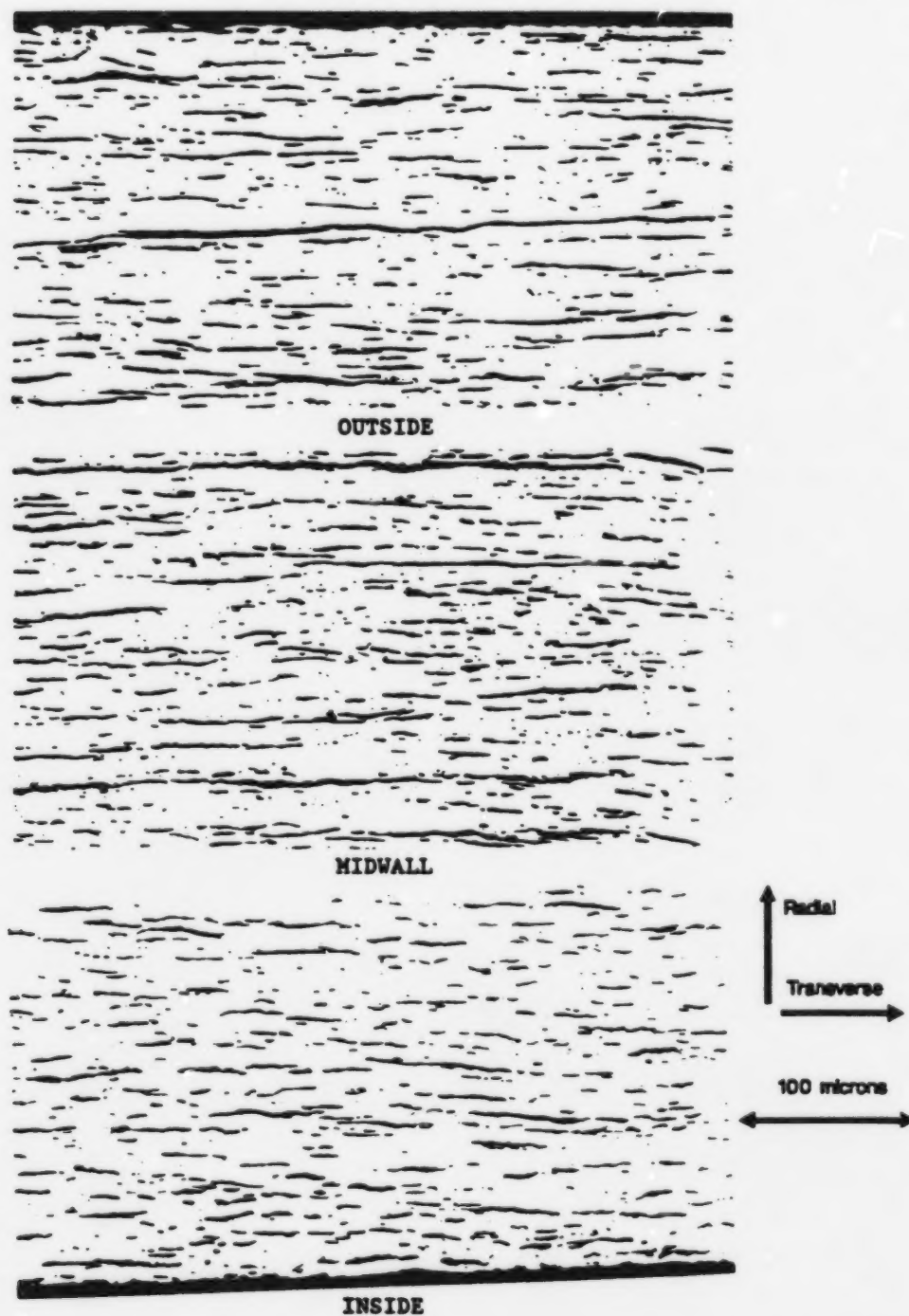


Figure 5: Representative outside, midwall and inside hydride distribution of the longitudinal section at 30.4 mm from the inlet end of the tube.

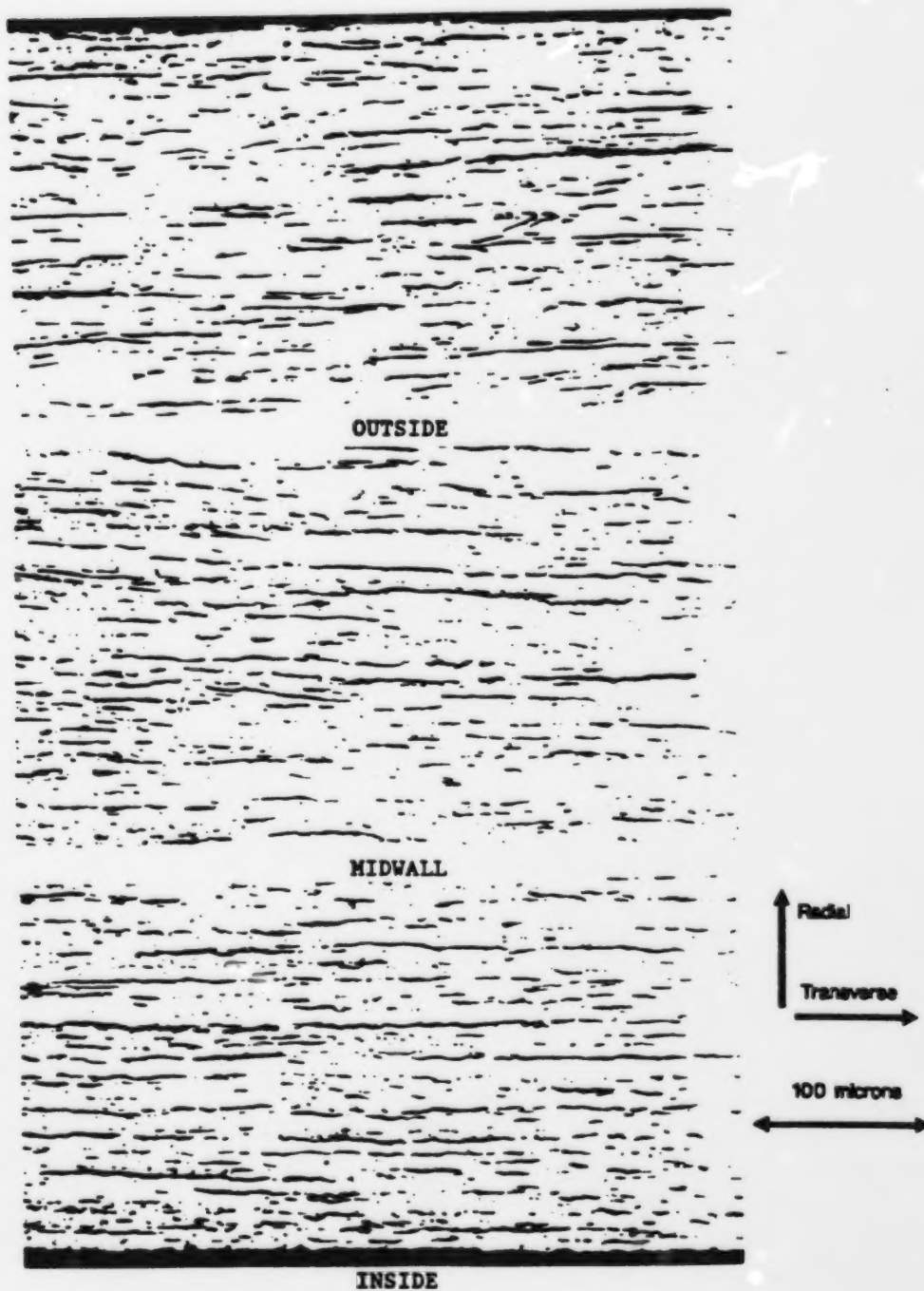


Figure 6: Representative outside, midwall and inside hydride distribution of the longitudinal section at 36.7 mm from the inlet end of the tube.

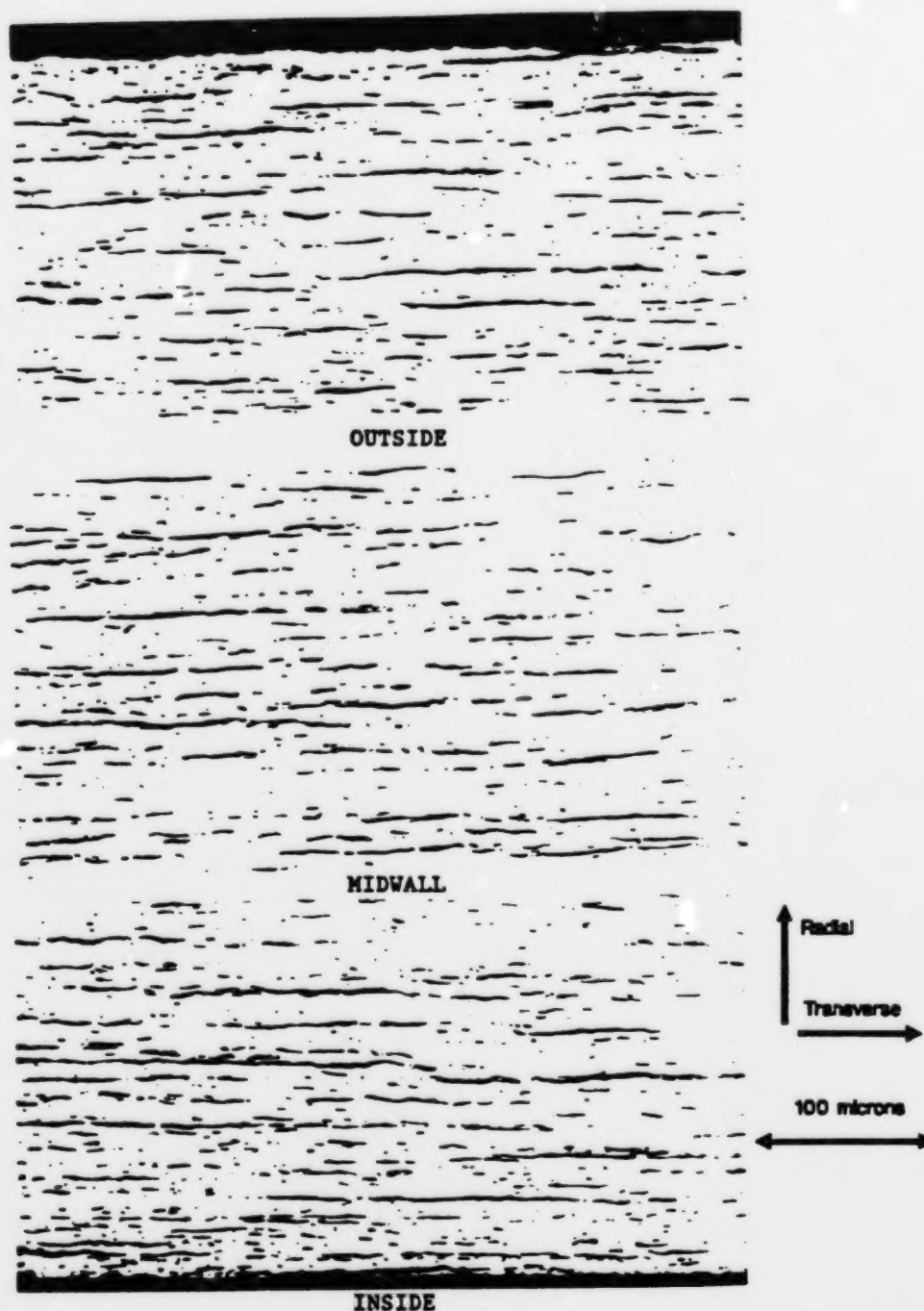


Figure 7: Representative outside, midwall and inside hydride distribution of the longitudinal section at 51.4 mm from the inlet end of the tube.

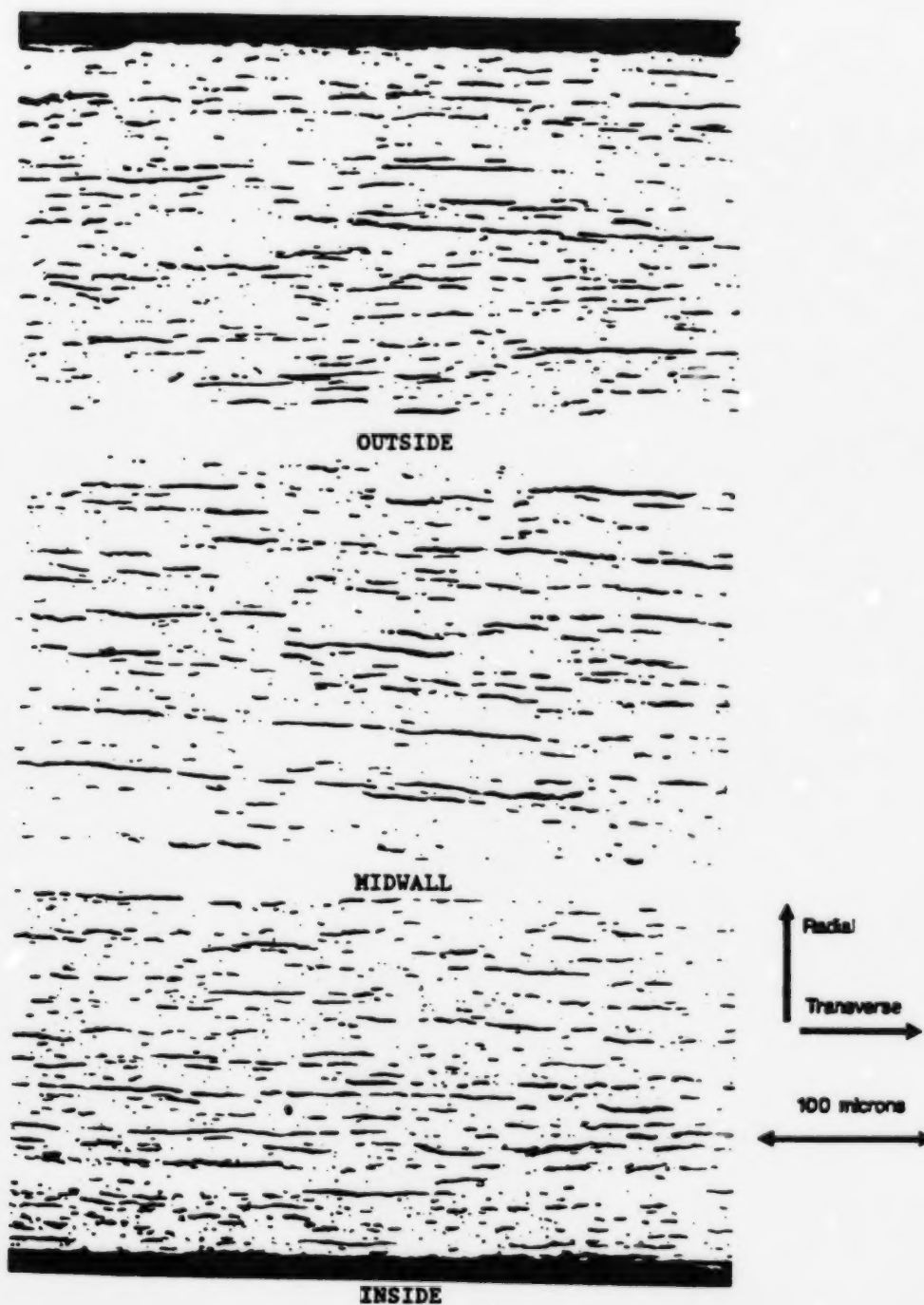


Figure 8: Representative outside, midwall and inside hydride distribution of the longitudinal section at 56 mm from the inlet end of the tube.

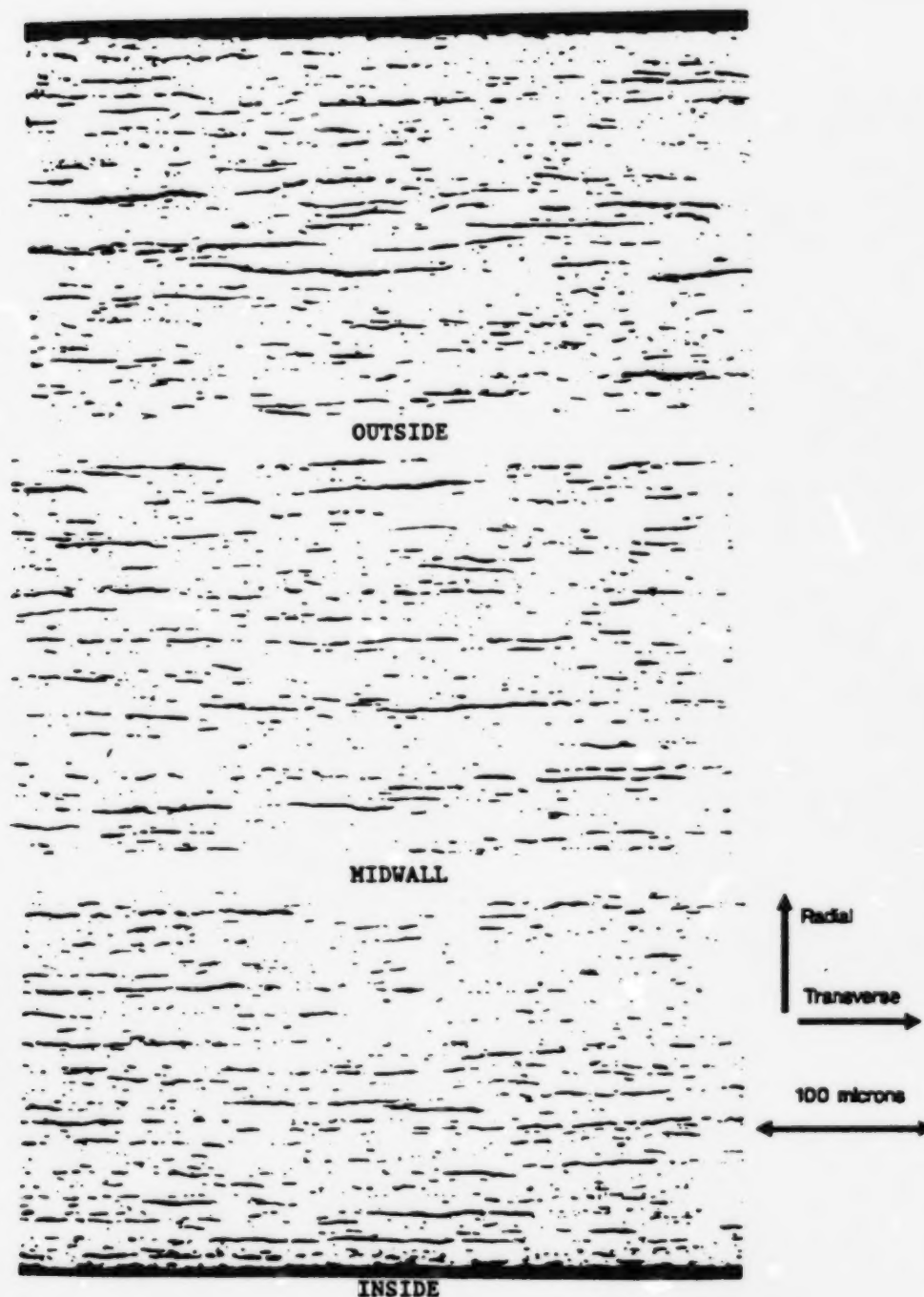


Figure 9: Representative outside, midwall and inside hydride distribution of the longitudinal section at 69 mm from the inlet end of the tube.

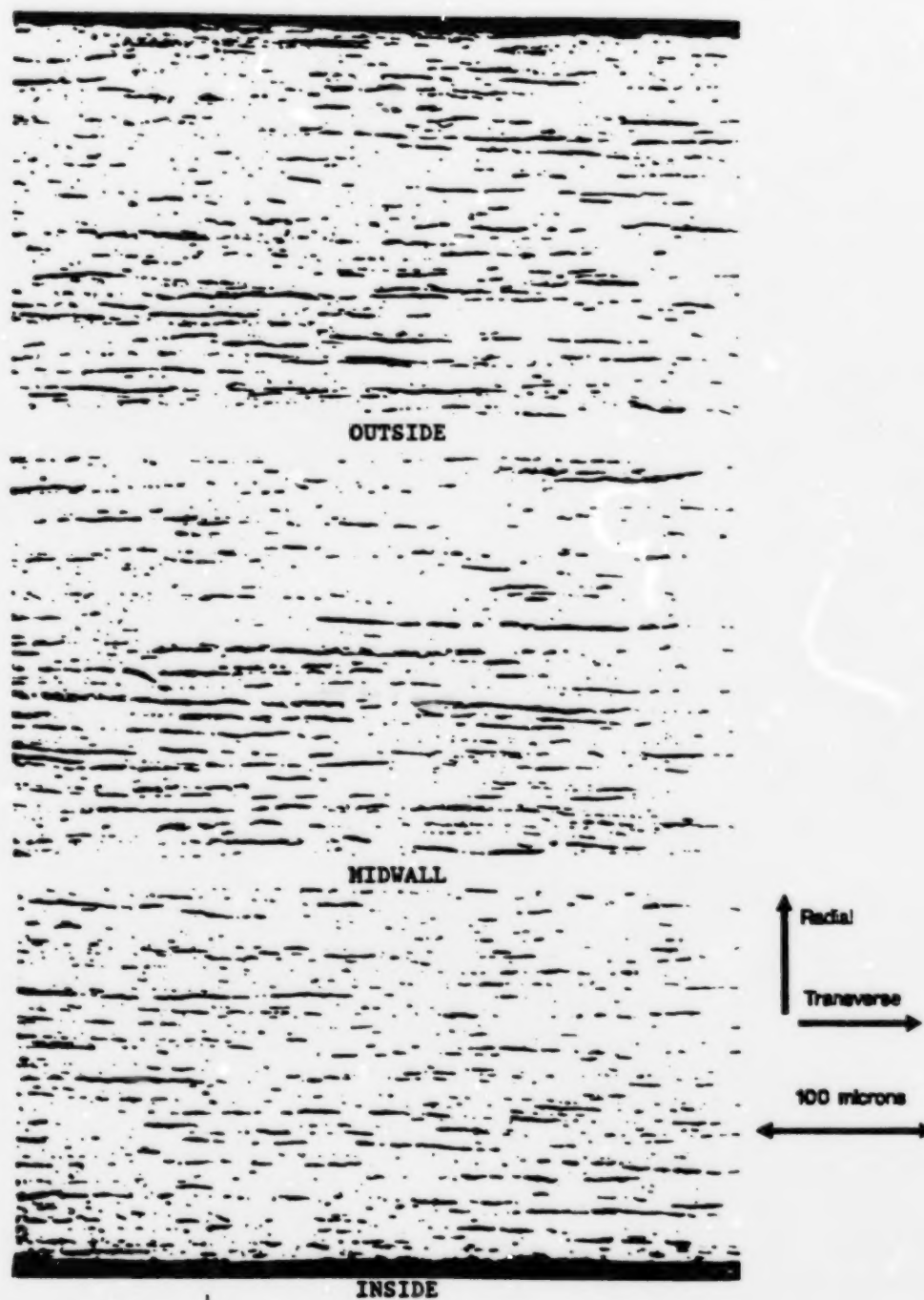


Figure 10: Representative outside, midwall and inside hydride distribution of the longitudinal section at 75.6 mm from the inlet end of the tube.

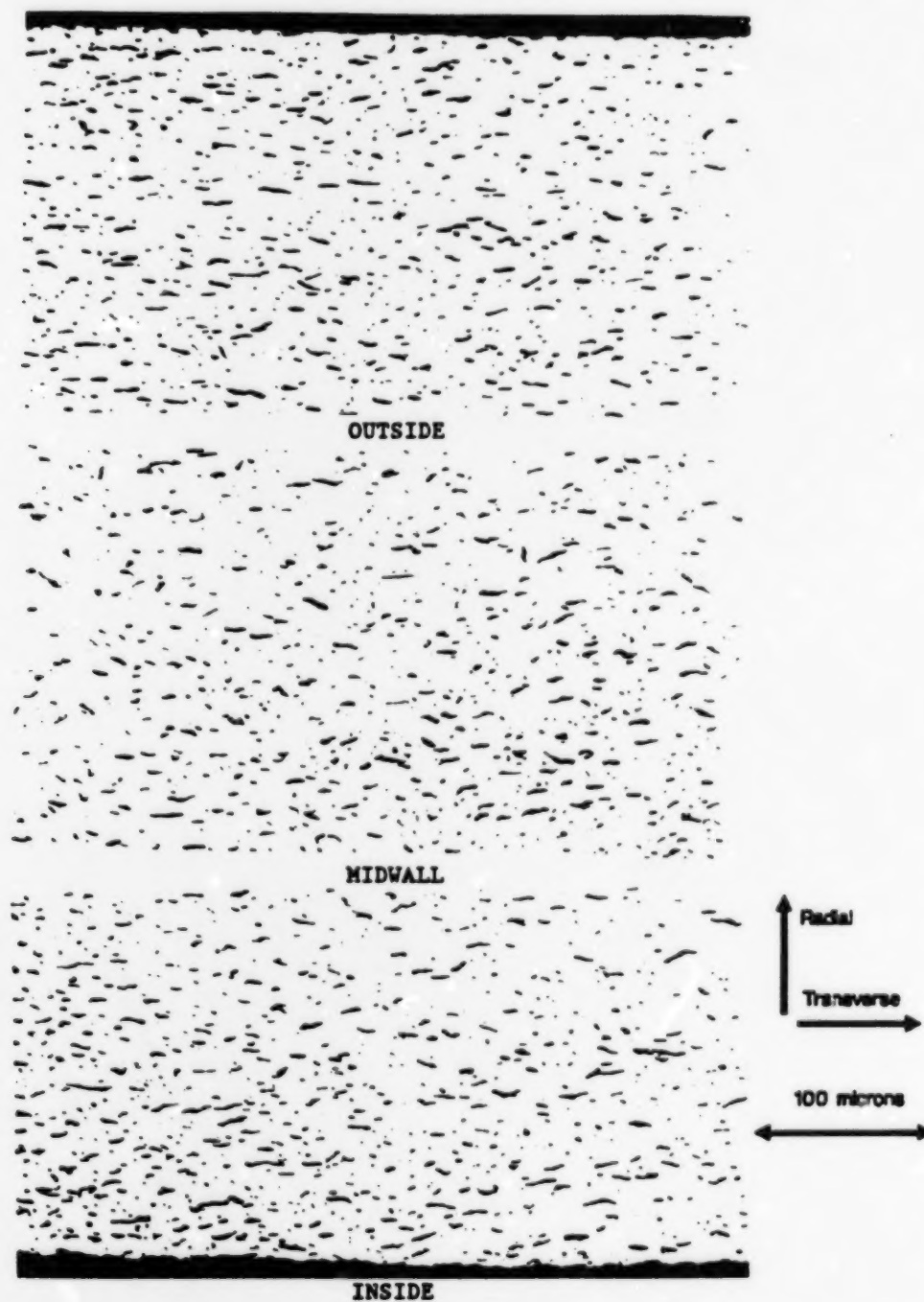


Figure 11: Representative outside midwall and inside hydride distribution of the transverse section at the inboard edge of the third rolling groove.

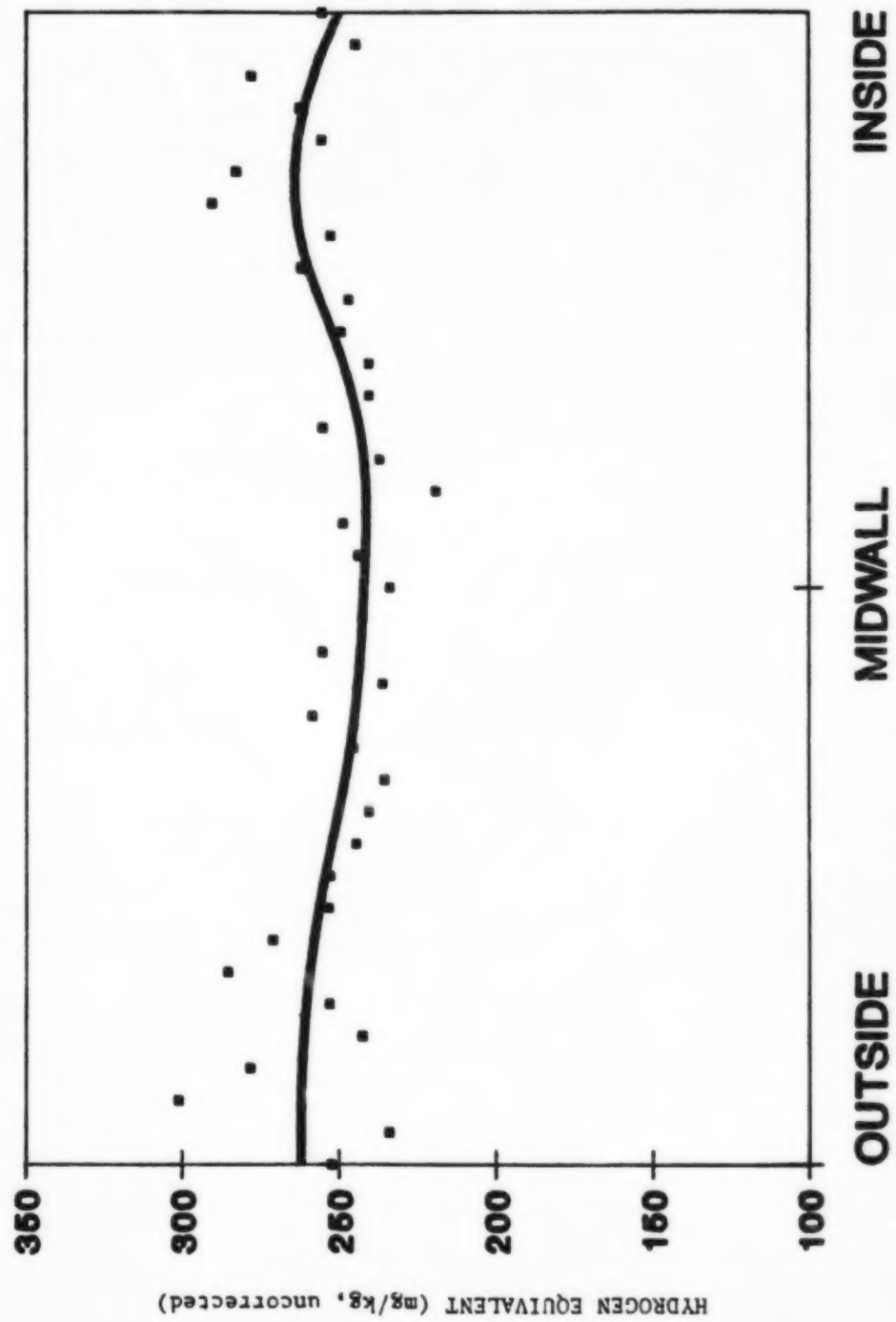


Figure 12. Image analysis results at 12.9 mm from the inlet end of the pressure tube.

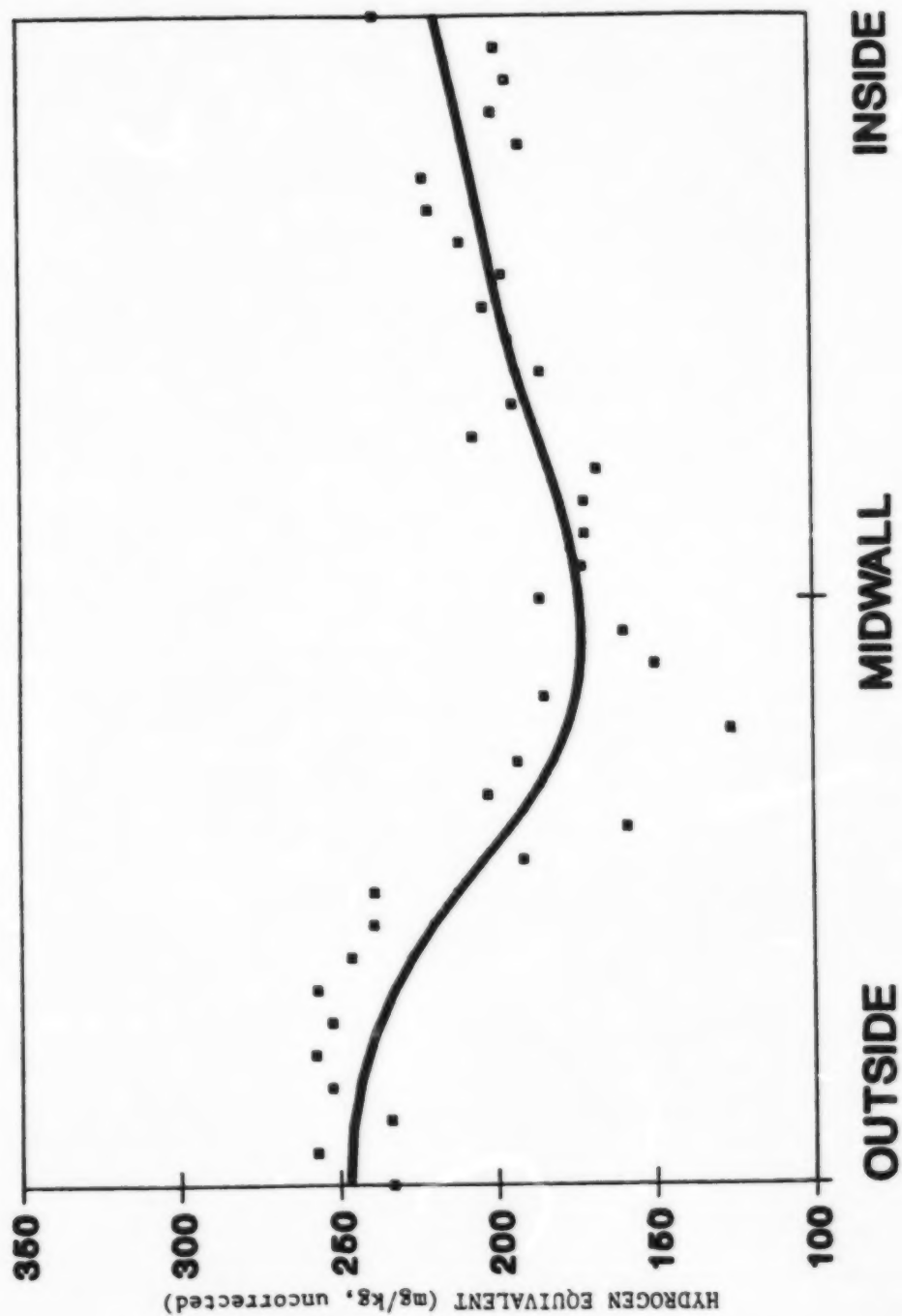


Figure 13. Image analysis results of 19.6 mm from the inlet end of the pressure tube.

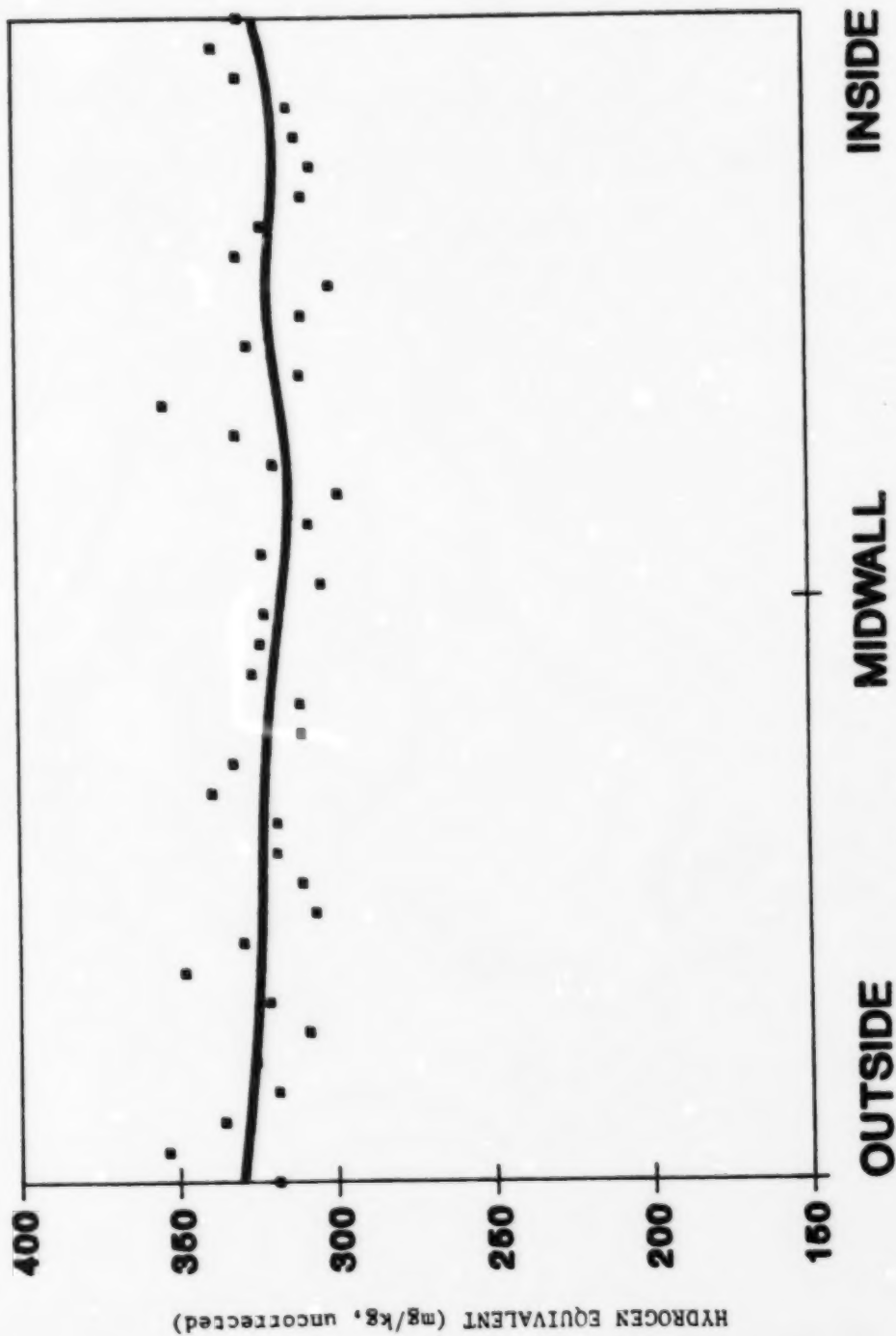


Figure 14. Image analysis results at 30.4 mm from the inlet end of the pressure tube.

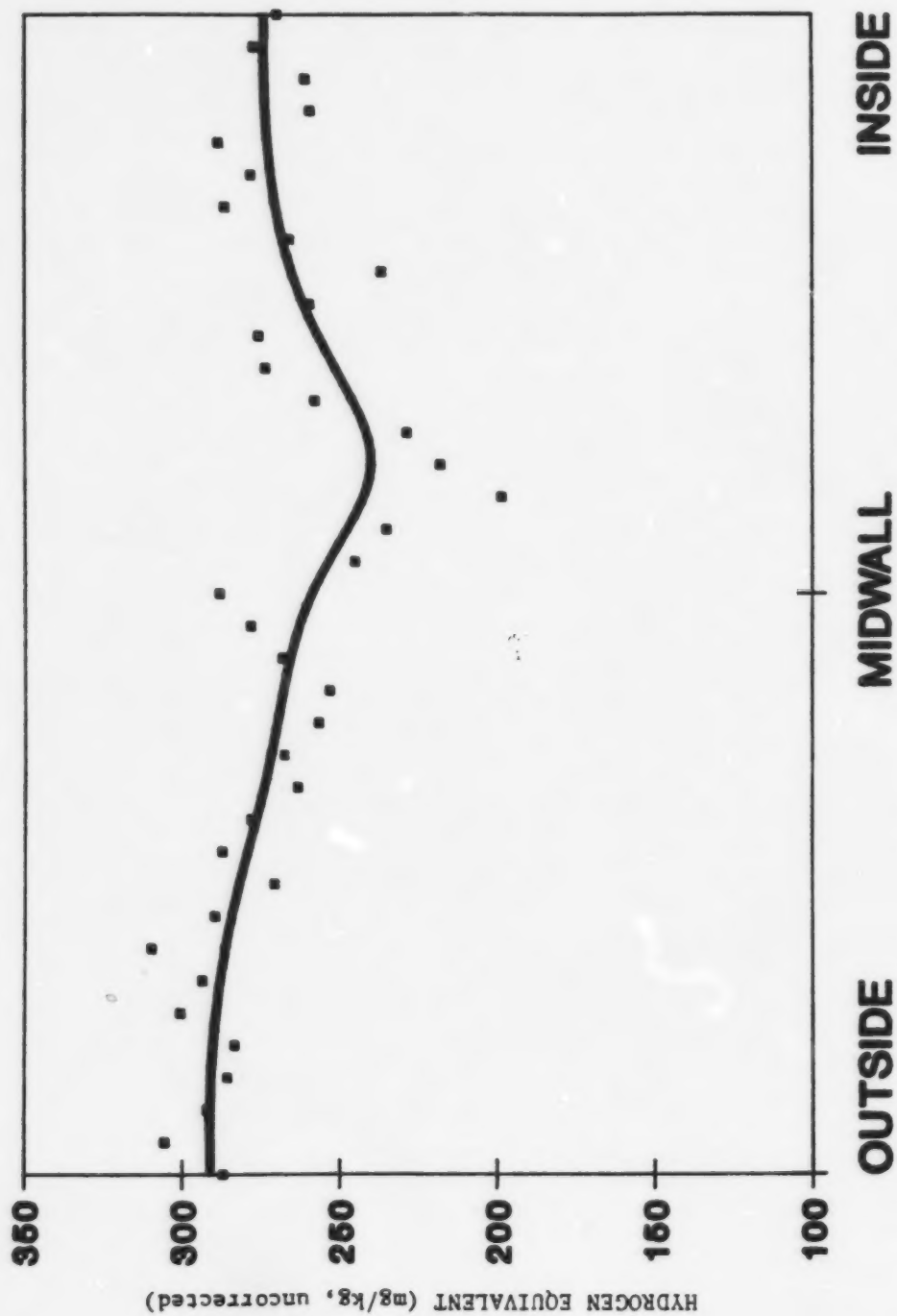


Figure 15. Image analysis results at 36.7 mm from the inlet end of the pressure tube.

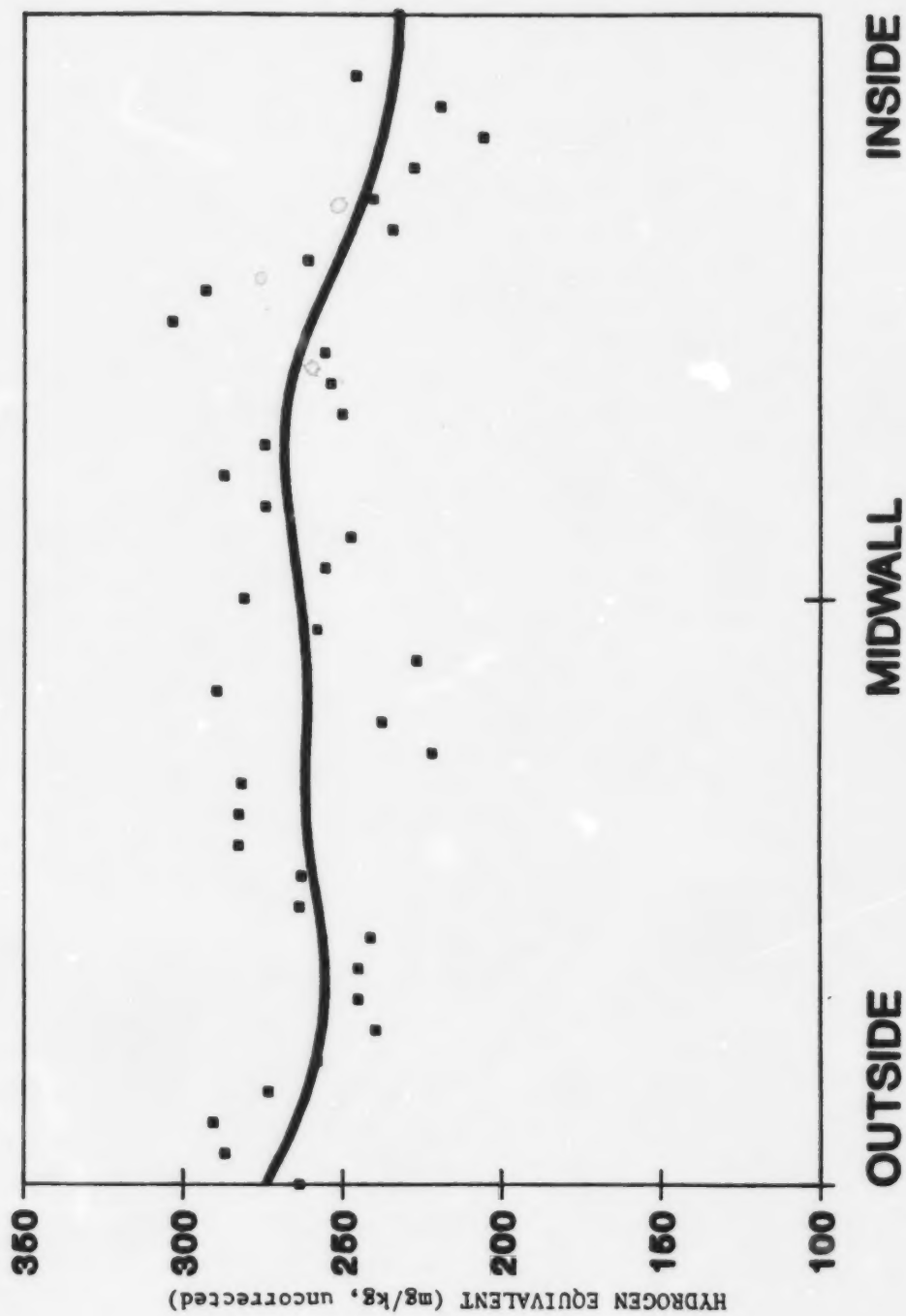


Figure 16. Image analysis results at 51.4 mm from the inlet end of the pressure tube.

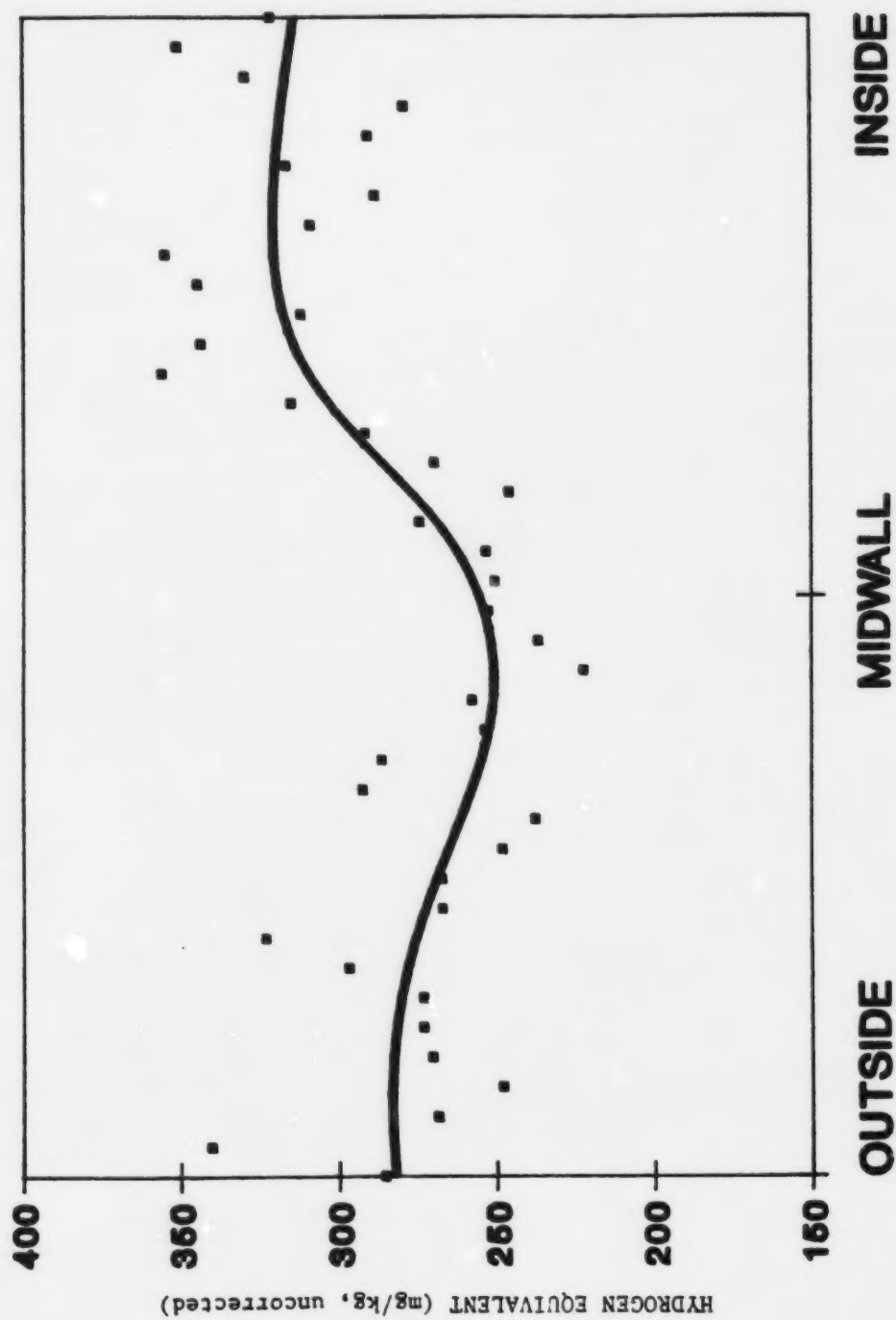


Figure 17. Image analysis results at 56.0 mm from the inlet end of the pressure tube.

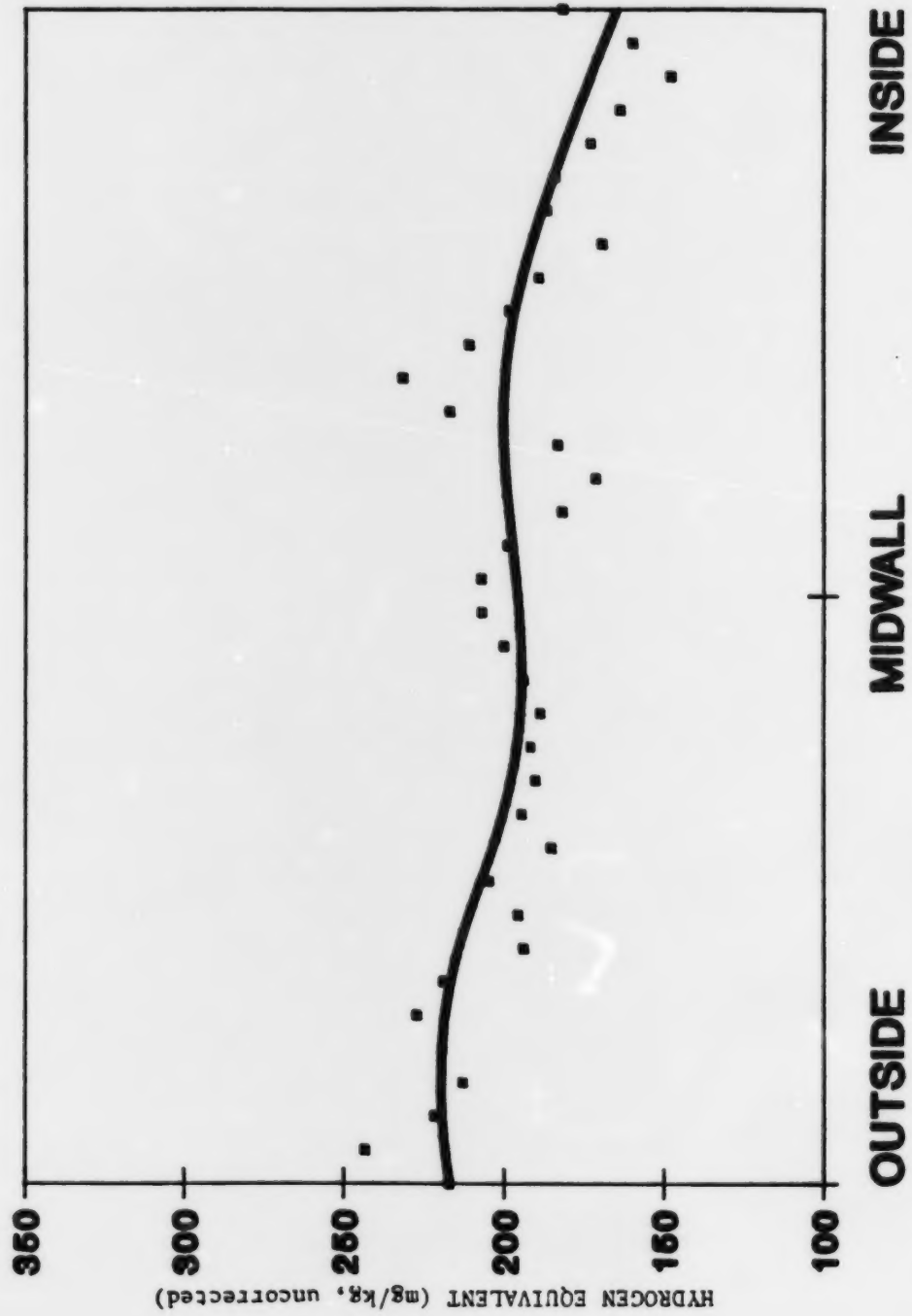


Figure 18. Image analysis results at 69.0 mm from the inlet end of the pressure tube.

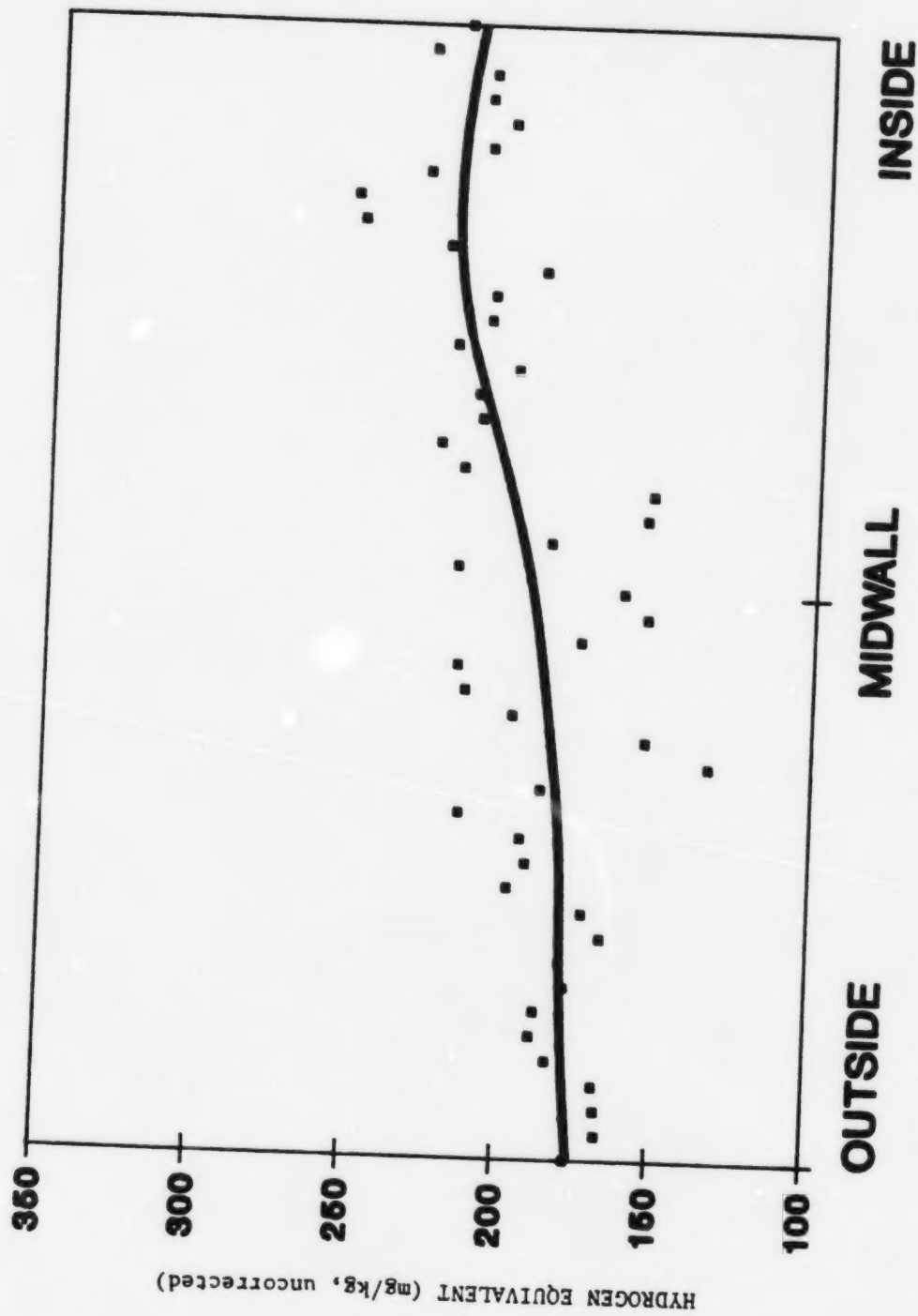
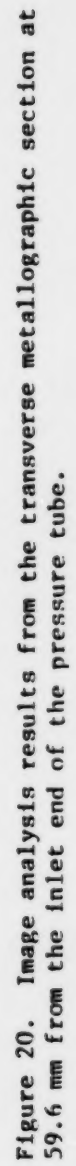


Figure 19. Image analysis results at 75.6 mm from the inlet end of the pressure tube.



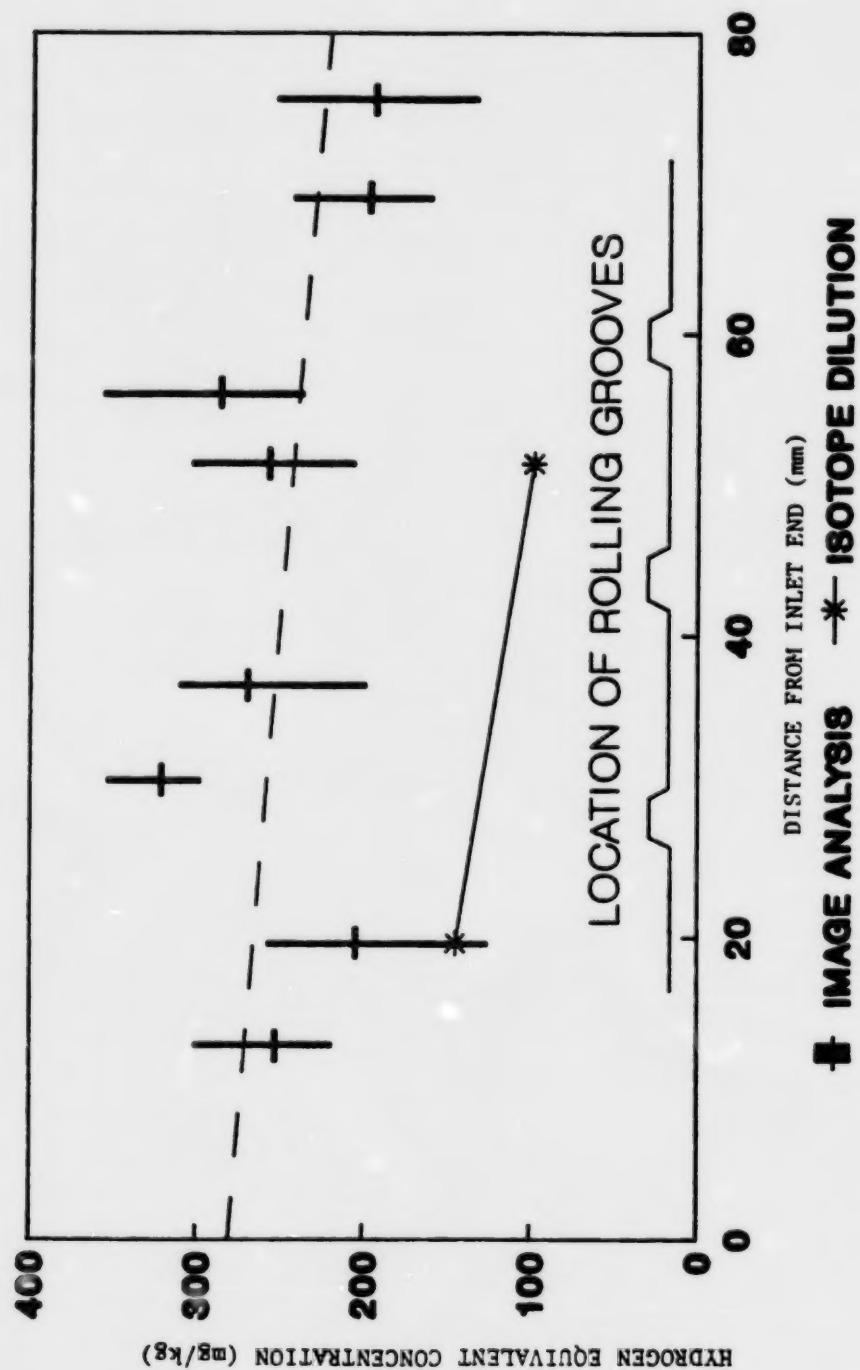


Figure 21. Hydrogen equivalent concentration values obtained from image analysis and isotope dilution. The dashed line is the linear regression of the average image analysis values.

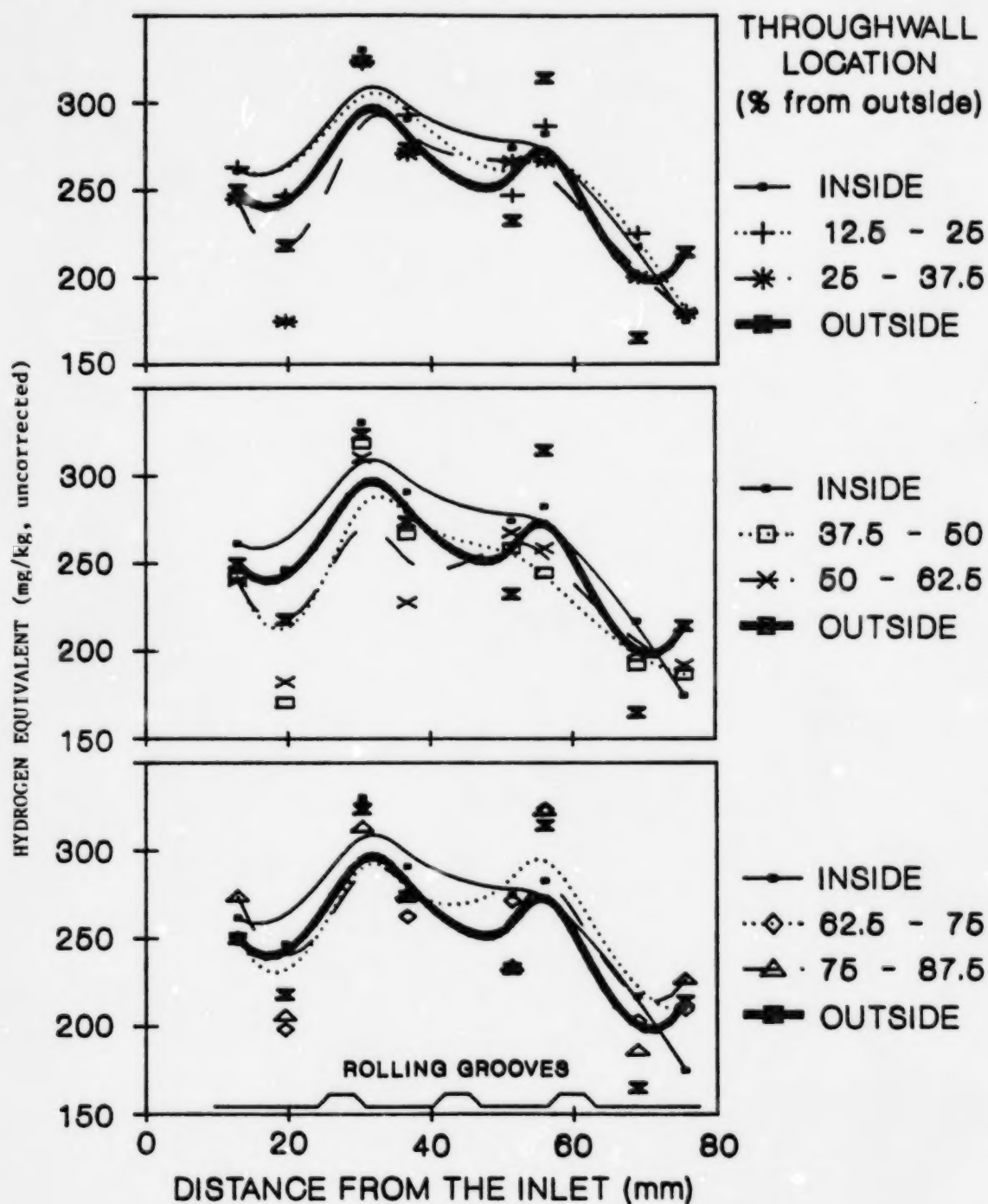


Figure 22. Average of through-wall segments of image analysis data.